

Mass segregation trends in SDSS galaxy groups

Ian D. Roberts*, Laura C. Parker, Gandhali D. Joshi and Fraser A. Evans

Department of Physics and Astronomy, McMaster University, Hamilton ON L8S 4M1, Canada

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ABSTRACT

It has been shown that galaxy properties depend strongly on their host environment. In order to understand the relevant physical processes driving galaxy evolution it is important to study the observed properties of galaxies in different environments. Mass segregation in bound galaxy structures is an important indicator of evolutionary history and dynamical friction timescales. Using group catalogues derived from the Sloan Digital Sky Survey Data Release 7 (SDSS DR7) we investigate mass segregation trends in galaxy groups at low redshift. We investigate average galaxy stellar mass as a function of group-centric radius and find evidence for weak mass segregation in SDSS groups. The magnitude of the mass segregation depends on both galaxy stellar mass limits and group halo mass. We show that the inclusion of low mass galaxies tends to strengthen mass segregation trends, and that the strength of mass segregation tends to decrease with increasing group halo mass. We find the same trends if we use the fraction of massive galaxies as a function of group-centric radius as an alternative probe of mass segregation. The magnitude of mass segregation that we measure, particularly in high-mass haloes, indicates that dynamical friction is not acting efficiently.

Key words: galaxies: clusters: general – galaxies: evolution – galaxies: groups: – galaxies: statistics

1 INTRODUCTION

It has been well established that galaxy properties depend strongly on local environment (e.g. Oemler 1974; Hogg et al. 2004; Blanton et al. 2005; Tal et al. 2014). Galaxies in dense environments such as clusters tend to have lower star formation rates (SFRs), while isolated field galaxies are generally actively forming stars (e.g. Balogh, Navarro & Morris 2000; Ball, Loveday & Brunner 2008; Wetzel, Tinker & Conroy 2012). It is also well known that galaxy properties, like SFR, depend strongly on galaxy mass (e.g. Poggianti et al. 2008). It is critical to study the distribution of galaxy masses within haloes of different masses in order to ascertain whether the variations in galaxy properties with environment are due to physical mechanisms acting in dense environments, or simply due to the fact that high density environments contain more high mass galaxies. Intermediate density environments, galaxy groups, represent not only the most common environment in the local universe (Geller & Huchra 1983; Eke et al. 2005), but also represent the environment where many physical processes are efficient. Galaxy interactions like mergers and harassment are favoured in this environment because of the low relative velocities between galaxies (Zabludoff & Mulchaey 1998; Brough et al. 2006).

The study of mass segregation in groups can be used

to elucidate information on physical processes such as dynamical friction, galaxy mergers, and tidal stripping. Mass segregation in bound structures has generally been predicted as a result of dynamical friction (Chandrasekhar 1943). Dynamical friction acts as a drag force on orbiting bodies and massive galaxies within groups and clusters are expected to migrate to smaller radii as time progresses. If dynamical friction is a dominant factor then clear mass segregation should be observable in evolved groups and clusters.

Galaxy groups are not static systems, but are constantly being replenished by infalling galaxies from the field. Infalling galaxies are preferentially found at large radii (Wetzel et al. 2013) and the difference in stellar mass distributions between evolved group members and infalling galaxies could affect the strength of mass segregation.

If significant mass segregation is not found, then this implies that either: the timescale associated with dynamical friction is greater than the age of the group/cluster, or that there are other physical processes, such as merging, tidal stripping, or pre-processing, which are playing a more important role than dynamical friction.

Recent work has shown conflicting results with regards to the presence of mass segregation in groups and clusters. Ziparo et al. (2013) find no evidence for strong mass segregation in X-ray selected groups from the ECDFS, COSMOS, GOODS-North, and GOODS-South fields out to $z = 1.6$, for a sample of galaxies with $M_{\text{star}} > 10^{10.3} M_{\odot}$.

* E-mail: roberid@mcmaster.ca

von der Linden et al. (2010) examine SDSS galaxy clusters and find no evidence for mass segregation in four different redshift bins at $z < 0.1$. von der Linden et al. make redshift dependent stellar mass cuts ranging from $10^{9.6} M_{\odot}$ to $10^{10.5} M_{\odot}$. Vulcani et al. (2013) use mass limited samples at $0.3 \leq z \leq 0.8$ from the IMACS Cluster Building Survey and the ESO Distant Cluster Survey, with stellar mass cuts at $M_{\text{star}} > 10^{10.5} M_{\odot}$ and $M_{\text{star}} > 10^{10.2} M_{\odot}$ respectively, to study galaxy stellar mass functions in different environments. Vulcani et al. find no statistical differences between mass functions of galaxies located at different cluster-centric distances.

Conversely, Balogh et al. (2014) find evidence for mass segregation in GEEC2 groups at $0.8 < z < 1$, using a stellar mass limited sample with $M_{\text{star}} > 10^{10.3} M_{\odot}$. Using a volume limited sample of zCOSMOS groups Presotto et al. (2012) find evidence for mass segregation in their whole sample at both $0.2 \leq z \leq 0.45$ and $0.45 \leq z \leq 0.8$. Presotto et al. also break their sample into rich and poor groups at $0.2 \leq z \leq 0.45$, and find evidence for mass segregation within rich groups but find no evidence for mass segregation within poor groups. Using a V_{max} weighted sample with a stellar mass cut at $10^{9.0} M_{\odot}$, van den Bosch et al. (2008) find evidence for mass segregation in SDSS groups.

It is clear that there lacks consensus with regards to the strength of mass segregation, or its halo mass dependence.

In this letter we present evidence of the presence of a small, but significant, amount of mass segregation in SDSS galaxy groups. We show that the detection of mass segregation is dependent on stellar mass completeness, with completeness cuts at relatively high stellar masses potentially masking underlying mass segregation trends. We also show that the strength of mass segregation scales inversely with halo mass, with cluster sized haloes showing little to no observable mass segregation. In § 2 we briefly describe our data set, in § 3 we present our results from this work, in § 4 we provide a discussion of our results, and in § 5 we give a summary of the results and make concluding statements.

In this letter we assume a flat Λ CDM cosmology with $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 DATA

The results presented in this letter utilize the group catalogue of Yang et al. (2007). This catalogue is constructed by applying the halo-based group finder of Yang et al. (2005, 2007) to the New York University Value-Added Galaxy Catalogue (NYU-VAGC; Blanton et al. 2005), which is based on the Sloan Digital Sky Survey Data Release 7 (SDSS DR7; Abazajian et al. 2009). Stellar masses are obtained from the NYU-VAGC and are computed using the methodology of Blanton & Roweis (2007), assuming a Chabrier (2003) initial mass function. Halo masses are determined using the ranking of the characteristic stellar mass, $M_{*, \text{grp}}$, and assuming a relationship between M_{halo} and $M_{*, \text{grp}}$ (Yang et al. 2007). $M_{*, \text{grp}}$ is defined by Yang et al. as

$$M_{*, \text{grp}} = \frac{1}{g(L_{19.5}, L_{\text{lim}})} \sum_i \frac{M_{\text{star}, i}}{C_i}, \quad (1)$$

where $M_{\text{star}, i}$ is the stellar mass of the i^{th} member galaxy, C_i is the completeness of the survey at the position of that

galaxy, and $g(L_{19.5}, L_{\text{lim}})$ is a correction factor which accounts for galaxies missed due to the magnitude limit of the survey.

Halo-centric distance for each galaxy is not given explicitly in the Yang catalog, however we calculate it using the redshift of the group and the angular separation of the galaxy and halo centre on the sky. We measure group-centric radius from the luminosity weighted centre of each group, and normalize our group-centric radii by R_{200} . We use the definition for R_{200} as given in Carlberg et al. (1997)

$$R_{200} = \frac{\sqrt{3}\sigma}{10H(z)}, \quad (2)$$

where the Hubble parameter, $H(z)$, is defined as

$$H(z) = H_0 \sqrt{\Omega_M(1+z)^3 + \Omega_{\Lambda}}, \quad (3)$$

and we calculate the velocity dispersion, σ , as

$$\sigma = 397.9 \text{ km s}^{-1} \left(\frac{M_{\text{halo}}}{10^{14} h^{-1} M_{\odot}} \right)^{0.3214}, \quad (4)$$

where the above is a fitting function given in Yang et al. (2007).

For our analysis we select group galaxies with redshift, $z < 0.1$, that are within two virial radii of the group centre, and groups with a minimum of three galaxy members – although our results are not sensitive to these specific cuts. For our sample over 95 per cent of group galaxies reside within two virial radii of the group centre. We also subtract the most massive galaxy (MMG) from each group, to ensure that any underlying radial mass trend is not contaminated by the MMG.

This sample is not volume limited, therefore the sample will suffer from Malmquist bias. This leads to a bias towards objects of higher luminosity and stellar mass, with increasing redshift. To account for this bias we weight our sample by $1/V_{\text{max}}$, where V_{max} is the comoving volume of the universe out to a comoving radius at which the galaxy would have met the selection criteria for the sample. For our V_{max} weights we apply the values presented in the catalogue of Simard et al. (2011) to our sample.

In order to investigate the effect of stellar mass limits on the detection of mass segregation, we use samples corresponding to various stellar mass cuts. We perform our analysis on an unweighted sample with two mass cuts corresponding to $M_{\text{star}} > 10^{10.5} M_{\odot}$ (4152 galaxies in 1970 groups) and $M_{\text{star}} > 10^{10.0} M_{\odot}$ (26774 galaxies in 4534 groups), and a V_{max} weighted sample with mass cuts at $M_{\text{star}} > 10^{9.0} M_{\odot}$ (56957 galaxies in 7217 groups) and $M_{\text{star}} > 10^{8.5} M_{\odot}$ (59791 galaxies in 7289 groups). The unweighted sample is stellar mass complete down to $M_{\text{star}} > 10^{10.0} M_{\odot}$. Therefore, for both the weighted and unweighted sample, we have two different stellar mass cuts, giving us four separate samples in total.

3 RESULTS

3.1 Mass segregation in SDSS groups

In Fig. 1 we plot mean stellar mass as a function of radial distance from the group centre for various halo mass bins.

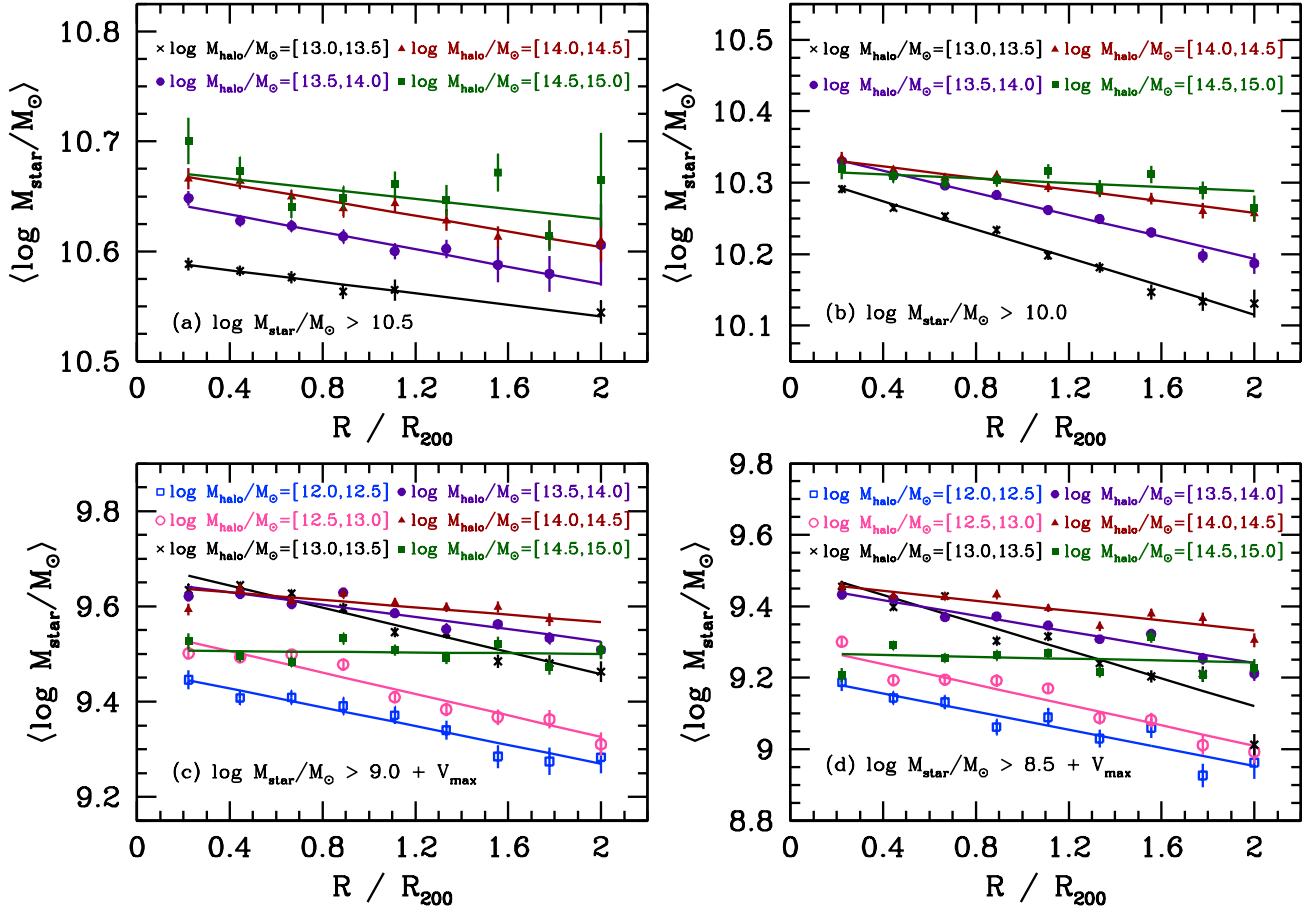


Figure 1. All panels show mean mass as a function of normalized radial distance for various halo mass bins, with error bars corresponding to 1σ statistical errors. The solid lines correspond to weighted least-squares fits for each halo mass bin. *Top left:* Unweighted sample, for galaxies with $\log(M_{\text{star}}/M_{\odot}) > 10.5$. *Top right:* Unweighted sample, for galaxies with $\log(M_{\text{star}}/M_{\odot}) > 10.0$. *Bottom left:* V_{max} weighted sample, for galaxies with $\log(M_{\text{star}}/M_{\odot}) > 9.0$. *Bottom Right:* V_{max} weighted sample, for galaxies with $\log(M_{\text{star}}/M_{\odot}) > 8.5$. Note that different mass scales are used in each panel. There are more halo mass bins in the bottom row due to the increased number of low mass galaxies as a result of V_{max} weighting.

Fig. 1a corresponds to our high-mass cut, unweighted sample, Fig. 1b corresponds to our low-mass cut, unweighted sample, Fig. 1c corresponds to our high-mass cut, weighted sample, and Fig. 1d corresponds to our low-mass cut, weighted sample.

For all halo mass bins, and regardless of mass cut, the unweighted sample shows statistically significant mass segregation with a weighted linear least-squares fit. The V_{max} weighted sample shows statistically significant mass segregation for the five lower halo mass bins, whereas the highest halo mass bin has a best-fitting slope consistent with zero – this trend holds for both mass cuts. For both the weighted and unweighted samples there is a clear trend of the slope with halo mass – more massive haloes show weaker mass segregation. This result will be discussed in § 4.2.

We find that our highest halo mass sample ($M_{\text{halo}} > 10^{14.5} M_{\odot}$) has a large number of low mass galaxies when compared to the high halo mass samples, which leads to a smaller mean stellar mass in the V_{max} weighted results shown in Fig. 1c & 1d. While this introduces a shift in normalization, it does not affect the mass segregation trend and

therefore does not change the key result that mass segregation depends on halo mass.

3.2 Massive galaxy fraction

An alternative way to investigate galaxy populations within the group sample is to study the fraction of ‘massive’ galaxies at various group-centric radii. In Fig. 2 we plot the fraction of massive galaxies as a function of radial distance. We calculate the massive fraction for each radial bin as

$$f_m(M_{\text{cut}}) = \frac{\# \text{ galaxies with } M_{\text{star}} > M_{\text{cut}}}{\# \text{ galaxies with } M_{\text{star}} > 10^{10} M_{\odot}}, \quad (5)$$

where M_{cut} is a stellar mass cut-off above which we define a massive galaxy. We initially apply a high mass galaxy cut, M_{cut} , at $10^{10.25} M_{\odot}$ corresponding to the median stellar mass of the unweighted sample (with the low-mass cut at $10^{10} M_{\odot}$). Comparing Fig. 2a and Fig. 1b we see essentially identical trends. We observe the same trends of mass segregation whether we look at the average galaxy mass at a given radius, or consider the fraction of massive galaxies.

To confirm that this trend is robust regardless of the mass cut-off used to define a massive galaxy, we make the

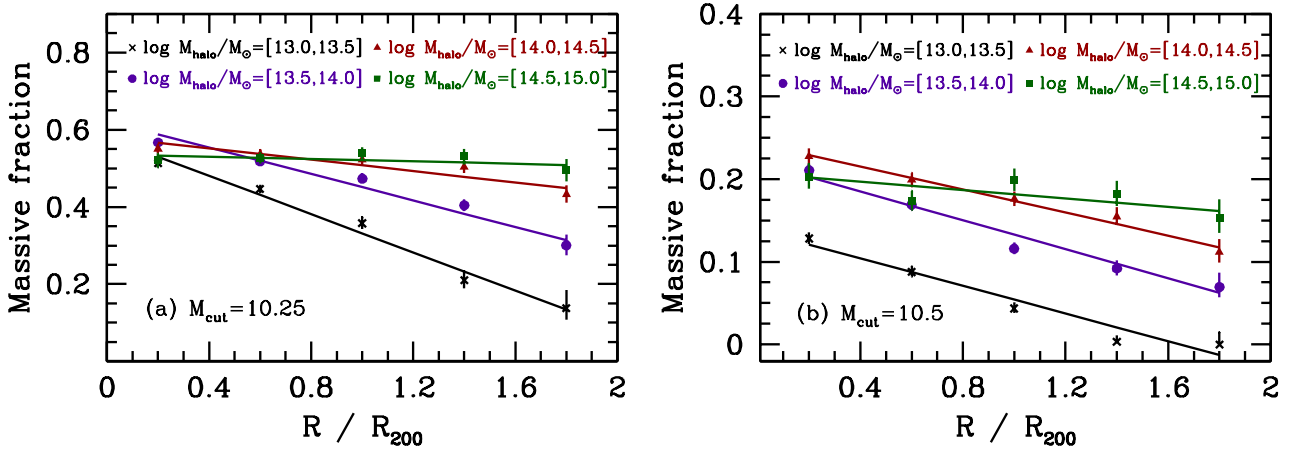


Figure 2. Fraction of massive galaxies with respect to normalized radial distance. Error bars are given by a 1σ binomial confidence interval, calculated using the beta distribution as outlined in Cameron (2011). The solid lines correspond to weighted least-squares fits for each halo mass bin. *Left panel:* The fraction of galaxies with $\log(M_{\text{star}}/M_{\odot}) > 10.25$ as a function of radial distance, for the unweighted sample with $M_{\text{star}} > 10^{10} M_{\odot}$. *Right panel:* The fraction of galaxies with $\log(M_{\text{star}}/M_{\odot}) > 10.5$ as a function of radial distance, for the unweighted sample with $M_{\text{star}} > 10^{10} M_{\odot}$.

same plot but now use $M_{\text{cut}} = 10^{10.5} M_{\odot}$. Comparing Fig. 2a and 2b we see that while the overall fractions of massive galaxies decrease with increasing the stellar mass cut, the trend essentially stays the same. There is clear evidence for mass segregation and the strength of the mass segregation depends on halo mass.

4 DISCUSSION

4.1 Effect of including low mass galaxies

The results in Fig. 1 show that mass segregation generally increases when lower mass galaxies are included. To quantify this effect we can compare the best-fitting slopes corresponding to the high-mass and the low-mass cut samples.

For a given halo mass, the low-mass cut sample displays larger slopes than the high-mass cut sample for two of the halo mass bins. The slopes corresponding to the other two halo mass bins are consistent with being equal. For the weighted sample we find similar results with the low-mass cut sample showing larger slopes for three of the halo mass bins, and the other three halo mass bins showing slopes consistent with being equal.

This suggests that the inclusion of low-mass galaxies has a measurable effect on the observation of mass segregation. Studies which make mass cuts at moderate to high stellar mass, are potentially missing a mass segregation contribution from low-mass galaxies. We note that these results are somewhat in disagreement with Ziparo et al. (2013) who find no mass segregation in their sample even with the inclusion of low-mass galaxies. The mass segregation we observe in Fig. 1 & 2 is very weak and the sample of Ziparo et al. may have been too small to show this subtle trend.

4.2 Halo mass dependence

Fig. 1 & 2 clearly indicate that the highest halo mass bins show the least mass segregation. This trend is consistent

in all cases, regardless of stellar mass cut or whether the sample had V_{max} weights applied. Our observed dependence on halo mass is consistent with results finding no measurable mass segregation in galaxy clusters (Pracy et al. 2005; von der Linden et al. 2010; Vulcani et al. 2013).

It has been shown through N-body simulations that the dynamical friction timescale scales with $M_{\text{h}}/M_{\text{s}}$ (e.g. Taffoni et al. 2003; Conroy, Ho & White 2007; Boylan-Kolchin, Ma & Quataert 2008), where M_{s} is the initial satellite mass and M_{h} is the mass of the host halo. For a given satellite mass, this implies a longer dynamical friction timescale for larger haloes, which is consistent with our result. This can be interpreted as an increase in tidal stripping efficiency as $M_{\text{h}}/M_{\text{s}}$ increases (Taffoni et al. 2003). Gan et al. (2010) have shown that for an infalling satellite the dynamical friction timescale increases with a stronger tidal field. This is due to tidal stripping retarding the decay of satellite angular momentum, which increases the dynamical friction timescale.

It should also be noted that the merger timescale scales with $M_{\text{s}}/M_{\text{h}}$ (Jiang et al. 2008), which implies a higher merger efficiency in low mass haloes, for a given satellite mass. The build-up of massive objects through galaxy mergers could enhance mass segregation in low-mass haloes, in accordance with our results.

There has been evidence of cluster galaxies having their star formation quenched in lower mass groups ($\sim 10^{13} M_{\odot}$) prior to accretion into the cluster environment (e.g. Zabludoff & Mulchaey 1998; McGee et al. 2009; De Lucia et al. 2012; Hou, Parker & Harris 2014). This pre-processing could potentially provide an explanation of our observed mass segregation trends with halo mass. If mass segregation is present in the group environment as a result of pre-processing, the recent accretion of multiple pre-processed groups to form a galaxy cluster could result in little to no observed mass segregation in the cluster as a whole. In other words, if the cluster environment consists of multiple subhaloes at various cluster-centric radii, while individual subhaloes may show mass segregation, the total

effect of these subhaloes together may leave the cluster with a relatively uniform radial mass distribution.

Vulcani et al. (2014) apply semi-analytic models to the Millenium Simulation (Springel et al. 2005) to study galaxy mass functions in different environments. Vulcani et al. simulate galaxy mass functions for three halo masses, $\log(M_{\text{halo}}/M_{\odot}) = \{13.4, 14.1, 15.1\}$, as a function of cluster-centric radius. In the lowest mass halo they find the mass function depends slightly on cluster-centric radius, with the innermost regions showing flatter mass functions at low and intermediate masses. This trend persists, but is not as strong at intermediate halo mass. The highest halo mass bin shows virtually identical mass function shapes for all cluster-centric radii. This result is indicative of measurable mass segregation for the low and intermediate mass haloes, with the strength of mass segregation decreasing with increasing halo mass. These simulation trends show excellent agreement with our observed dependence of mass segregation on halo mass.

4.3 Reconciling previous results

In § 1 we mention previous literature results which present evidence both for and against the presence of mass segregation in groups and clusters. We argue that the majority of these results can be reconciled with our two main findings:

- (i) Mass segregation is enhanced with the inclusion of low-mass galaxies in a sample.
- (ii) Mass segregation decreases with increasing halo mass, with high-mass haloes showing little to no mass segregation.

Of the studies mentioned in § 1, those which observe no evidence for mass segregation either: make a mass completeness cut at intermediate to high stellar mass, or observe this lack of mass segregation only in high-mass haloes. Therefore the lack of observed mass segregation can potentially be explained through the lack of low-mass galaxies in the study survey, or the study being limited to high halo mass environments.

5 CONCLUSION

In this letter we examine mass segregation trends in the Yang et al. (2007) SDSS DR7 groups for various stellar and halo mass cuts. We show that a small, but significant, amount of mass segregation is present in these groups. This mass segregation shows consistent trends, with lower stellar mass samples showing stronger mass segregation, and groups residing in large haloes showing little to no mass segregation.

The magnitude of mass segregation we measure, especially in high mass haloes, is potentially indicative of dynamical friction not acting efficiently. We discuss previous literature to provide possible explanations for the observed trends, showing that our observed trends with halo mass agree with prior results. Further work with hydrodynamic simulations would be helpful to further constrain the important mechanisms responsible for our observed mass trends and the lack of mass segregation in high-mass haloes.

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REFERENCES

- Abazajian K.N. et al., 2009, *ApJS*, 182, 543
- Ball N.M., Loveday J., Brunner R.J., 2008, *MNRAS*, 383, 907
- Balogh M.L. et al., 2014, *MNRAS*, 443, 2679
- Balogh M.L., Navarro J.F., Morris S.L., 2000, *ApJ*, 540, 113
- Blanton M.R., Roweis S., 2007, *AJ*, 133, 734
- Blanton M.R., Eisenstein D., Hogg D.W., Schlegel D.J., Brinkmann J., 2005, *ApJ*, 629, 143
- Blanton M.R. et al., 2005, *ApJ*, 129, 2562
- Boylan-Kolchin M., Ma C.P., Quataert E., 2008, *MNRAS*, 383, 93
- Brough S., Forbes D.A., Kilborn V.A., Couch W., 2006, *MNRAS*, 370, 1223
- Cameron E., 2011, *PASA*, 28, 128
- Carlberg R.G. et al., 1997, *ApJ*, 485, L13
- Chabrier G., 2003, *PASP*, 115, 763
- Chandrasekhar S., 1943, *ApJ*, 97, 255
- Conroy C., Ho S., White M., 2007, *MNRAS*, 379, 1491
- De Lucia G., Weinmann S., Poggianti B.M., Aragón-Salamanca A., Zaritsky D., 2012, *MNRAS*, 423, 1277
- Eke V.R., Baugh C.M., Cole S., Frenk C.S., King H.M., Peacock J.A., 2005, *MNRAS*, 362, 1233
- Gan J.L., Kang X., Hou J.L., Chang R.X., 2010, *MNRAS*, 10, 1242
- Geller M.J., Huchra J.P., 2010, *ApJS*, 52, 61
- Hogg D.W. et al., 2004, *ApJ*, 601, L29
- Hou A., Parker L.C., Harris W.E., 2014, *MNRAS*, 442, 406
- Jiang C.Y., Jing Y.P., Faltenbacher A., Lin W.P., Lin C., 2008, *ApJ*, 675, 1095
- Macciò A.V., Dutton A.A., van den Bosch F.C., Moore B., Potter D., Stadel J., 2007, *MNRAS*, 378, 55
- McGee S.L., Balogh M.L., Bower R.G., Font A.S., McCarthy I.G., 2009, *MNRAS*, 400, 937
- Oemler J. A., 1974, *ApJ*, 194, 1
- Poggianti B.M. et al., 2008, *ApJ*, 684, 888
- Pracy M.B., Driver S.P., De Propriis R., Couch W.J., Nulsen P.E.J., 2005, *MNRAS*, 364, 1147
- Presotto et al., 2012, *A&A*, 539, A55
- Simard L., Mendel J.T., Patton D.R., Ellison S.L., McConnachie A.W., 2011, *ApJS*, 196, 11

- Springel V. et al., 2005, *Nature*, 435, 629
- Taffoni G., Mayer L, Colpi M., Governato F., 2003, *MNRAS*, 341, 434
- Tal T. et al., 2014, *ApJ*, 789, 164
- van den Bosch F.C., Norberg P., Mo H.J., Yang X., 2004, 352, 1302
- van den Bosch F.C., Pasquali A., Yang X., Mo H.J., Weinmann S., McIntosh D.H., Aquino D., 2008, preprint (arXiv0805.0002)
- von der Linden A., Wild V., Kauffmann G., White S.D.M., Weinmann S., 2010, *MNRAS*, 404, 1231
- Vulcani B. et al., 2013, *A&A*, 550, A58
- Vulcani B., De Lucia G., Poggianti B.M., Bundy K., More S., Calvi R., 2014, *ApJ*, 788, 57
- Wetzel A.R., Tinker J.L., Conroy C., 2012, *MNRAS*, 424, 232
- Wetzel A.R., Tinker J.L., Conroy C., van den Bosch F.C., 2013, *MNRAS*, 432, 336
- Yang X., Mo H.J., van den Bosch F.C., Jing Y.P., 2005, *MNRAS*, 356, 1293
- Yang X., Mo H.J., van den Bosch F.C., Pasquali A., Li C., Barden M., 2007, *ApJ*, 671, 153
- Zabludoff A.I., Mulchaey J.S., 1998, *ApJ*, 496, 39
- Ziparo F. et al., 2013, *MNRAS*, 434, 3089